

# Radio Galaxies in Cooling Cores: Insights from a Complete Sample

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**Summary.** We have observed a new, complete, cooling-core sample with the VLA, in order to understand how the massive black hole in the central galaxy interacts with the local cluster plasma. We find that every cooling core is currently being energized by an active radio jet, which has probably been destabilized by its interaction with the cooling core. We argue that current models of cooling-core radio galaxies need to be improved before they can be used to determine the rate at which the jet is heating the cooling core. We also argue that the extended radio haloes we see in many cooling-core clusters need extended, *in situ* re-energization, which cannot be supplied solely by the central galaxy.

What heats cooling cores? The spotlight has turned on active galactic nuclei (AGN), driven by massive black holes in the heart of the galaxy at the center of the cooling core (CC). The jets in a few bright, well-studied radio galaxies (RGs) (*e.g.*, M87 [17]; A2052 [2]; Perseus A [9]) seem to be pouring out more than enough energy to offset radiative cooling in the CC in these clusters. But is this not the full answer; questions remain. Does every CC have a central RG? Is a typical cooling-core radio galaxy (CCRG) strong enough to offset local cooling? Does the energy carried by the jet couple effectively to the intracluster medium (ICM)? How can we use radio and X-ray data to estimate the jet power and energy input to the CC? To answer these questions, we must study more than the brightest few CCRGs, and must also look critically at dynamical models of the RG. We therefore carried out deep radio observations of a complete sample of CCRGs. In this paper we summarize our results and speculate on how to extend current models; more details will be given in [6].

## 1 The Data: What We Did

We formed a complete, X-ray selected sample of CCs in nearby Abell clusters. We started with ROSAT All-Sky Survey images of nearby ( $z < 0.09$ ) Abell clusters [14]. We identified clusters which are X-ray bright ( $L_x > 3 \times 10^{43}$  erg/s within a 500 kpc aperture), centered on a massive galaxy, and with a centrally concentrated X-ray atmosphere (ratio of flux within 500 and 62.5 kpc apertures no larger than  $\sim 14$ ). These criteria correlate well with strong CCs

found in other, more detailed deprojection analyses (*e.g.*, [19].) From these we selected clusters favorably placed in the sky for nighttime VLA observations in 2002. This procedure gave us 22 clusters: A85, A133, A193, A426, A496, A780, A1644, A1650, A1651, A1668, A1795, A1927, A2029, A2052, A2063, A2142, A2199, A2428, A2495, A2597, A2626 and A2670. Good, deep radio data already exist for 3 of these (A85; A426, the Perseus A cluster; A780, the Hydra A cluster). We observed the rest with the VLA. Because high-resolution radio data exist for many of these objects, we designed our observations to detect faint, extended radio emission [15]. We note that M87 is not in our formal sample, because it is not in an Abell cluster, and its CC is on the weak side. We include it in much of our analysis, however, because it is so well studied [17, 10], and it is an important example of the interaction between CCs and their embedded RGs. In addition, nine of our clusters were also included in our VLA search [15] for cluster-scale radio haloes, giving us additional information on extended emission from these objects.

## 2 The Data: what we have learned

Our data show that the story is more complicated than has been thought. We find evidence every that cooling core is being disrupted, and probably energized, by an AGN. Our data also suggest that the radio-loud plasma does mix with the ICM, at least on large scales, and that the AGN may well *not* be the only driver for the ICM in a cooling-core cluster.

### 2.1 Every Cooling Core Contains a Radio Source

Every cooling core in our sample contains a currently-active radio core (some too faint to have been detected in previous work). This means that the central AGN are active 100% of the time; they do not have any “off” periods. However, if current dynamical estimates of source ages ( $\sim 100$  Myr) are close to correct, the central AGN is probably variable, cycling through high-power and low-power states. The jet and inner halo of M87 [11] appear to be an example of a recently “reinvigorated” AGN.

It follows that every RG in a cooling-core is currently being driven by an active jet. In particular, our deep radio images sometimes reveal faint jets connecting the central AGN to what were previously thought to be offset “relics” (*e.g.*, A133, A2199). We therefore argue that very few CCRGs are simply passive, buoyant bubbles. The situation is more complex; we hope the data can guide us toward improved models.

### 2.2 The Radio Galaxies are Unusually Disturbed

Cooling-core RGs are characterized by unusual morphologies. Most of them are neither Fanaroff-Riley Type I (tailed), nor Type II (classical doubles).

Sixteen CCRGs in our sample are well enough imaged to reveal their structure (the remaining 7 are too faint and too small). Three of these 16 are standard tailed sources (including Hydra A). The rest are diffuse and amorphous. Such a large fraction (80% of the set) is far too many to be “normal” RGs seen end-on. Furthermore, amorphous sources such as these are rare in the general radio-galaxy population; only 5 of the  $\sim 200$  well-imaged cluster radio galaxies in the Owen-Ledlow set [18] are amorphous, and *all* of those sit in the centers of strong cooling cores.

These data show that an unusually strong interaction occurs between the radio jet and the dense cooling-core into which it tries to propagate. The interaction seems to destabilize the jet, on a scale of only a few kpc (the short jets in M87, Perseus A and A2052 are good examples here). It follows that the evolution of a cluster-core RG is not governed by directed momentum flux, in a large-scale jet, as is the case with most RGs. Instead, isotropized energy flow from a disrupted jet creates the amorphous haloes that we see. The strong RG-CC interaction is also suggestive of an effective energy transfer between the jet and the local cooling core; however the details of the process remain unclear.

### 2.3 The Radio Haloes Extend to Large Scales

Many of our CCRG are much larger than was previously known. Most of the amorphous sources have two scales of radio emission: a smaller, brighter source (often previously studied in higher resolution observations) is embedded within a larger, faint, extended mini-halo. Typical sizes of these mini-haloes range from  $\sim 70$  to 200 kpc. For instance, Per A [3] and A2029 [15] can be traced to  $\sim 200$  kpc, nearly as large as the long radio tails of Hyd A [13]. If the AGN is always “on”, but cycles between strong and weak states, the mini-haloes may be relics of previous activity cycles. In addition, we have detected Mpc-scale radio haloes in two clusters, A2328 and A2495, which refutes the current idea that Mpc-scale haloes avoid cooling cores.

To put these sizes in context, recall that the size of the cooling core is typically  $\sim 50$ – $100$  kpc. The size of the cluster’s potential well, as measured by the Navarro-Frenk-White scale radius, is only a few hundred kpc in CC clusters. Furthermore, the haloes do not obviously have clear edges. The sizes we measure are limited by the sensitivity of the observations, and may not be the true extent of the radio emission. With such large scales, the radio haloes may better be regarded as part of the entire ICM, not just a byproduct of the central AGN.

### 2.4 The Radio and X-ray Plasmas Must Mix

Our sample contains a variety of mixing states. Some of our clusters have small, clear X-ray cavities in the inner CC, approximately coincident with

the RG. These cavities are very likely filled by radio-loud plasma, with little or no X-ray plasma. In other clusters (*e.g.*, M87 [10], A1795 [7]), the interaction between the two plasmas is more complex. The X-ray plasma is clearly interacting with, but not evacuated by, the radio plasma. In still others, the X-ray plasma appears smooth and undisturbed on the scale of the RG, at the best current X-ray resolution and sensitivity. We suspect the two plasmas have at least partially mixed in these CCs. In addition, because the ICM is not dramatically disturbed on hundred-kpc scales, the larger radio haloes must be effectively mixed with the ICM.

It seems, therefore, that the radio and X-ray plasmas mix effectively during the lifetime of the CCRG. Just how this occurs is not clear, given the stabilizing effects of even a small magnetic field in the ICM [12]. Deep, high resolution radio images (*e.g.*, M87, [17]; A2199, in preparation) may provide hints. We see radio-loud filaments in these sources that appear to be escaping from the RG and penetrating the CC plasma. These filaments may be similar to the magnetic flux ropes which are known to penetrate the terrestrial magnetopause. Such flux ropes, once formed, may decouple from the main body of the radio source and rise buoyantly through the ICM, giving rise to an extended radio halo coincident with a relatively smooth X-ray atmosphere.

### 3 The Models: Where to Go Next

The important question in the context of this meeting is, how much energy does a “typical” central AGN deposit in the cooling core plasma? To answer this, we must determine the mean jet power,  $P_j$ , averaged over the lifetime of a typical CCRG, and how effectively that power is deposited in the local plasma. We emphasize that we have *no* direct measure of  $P_j$ . The radio power of the CCRG is a poor tracer of the jet power [5]. The best we can do directly from observations is to use minimum-pressure arguments, which are possible if the jet is resolved (*e.g.* M87 [17]). This gives us a lower bound on  $P_j$ . To go further, we must choose a dynamical model for the RG and its interaction with the local ICM. This sounds simple, but the devil is in the details.

#### 3.1 Calorimetry

The simplest cases are cooling cores which have clear X-ray cavities that coincide with an extended RG. In these the mean jet power can be found from the energy within the cavity and the age of the source. This is a simple, attractive approach, which has been applied by various authors (*e.g.*, [1, 4]). However, it has complications. One is that measuring the energy content of the cavity is not straightforward, because it is hard to know the extent to which the radio and X-ray plasmas have mixed in most of these clusters. A second concern is how to estimate the age of the source. Most authors currently assume the radio source is passive, having been previously inflated

by an AGN which has since turned off. If this holds, the source age is its size divided by the bouyant speed,  $v_b$ . But what is  $v_b$ ? The sound speed is no more than an optimistic upper limit, because  $v_b$  is quite subsonic for small structures. In addition, magnetic tension from even a very small intracluster field can exceed hydrodynamic drag, and reduce  $v_b$  even more [12].

A more serious concern, however, is the evidence from our work that every CCRG is currently being driven by jets from an active AGN, and that large-scale radio haloes have mixed with the ICM. It follows that very few CCRGs are well described as isolated, passive, buoyant bubbles (although buoyancy surely plays some role in the evolution of the RG). New models are needed.

### 3.2 Possible Dynamical Models

As a first step towards such new models, we suggest that CCRG evolution can be broken into two stages. We envision an early stage in which young, driven sources interact with and expand into the ICM, and a later stage in which the RGs have grown into extended mini-haloes mixed with the ICM. If AGN activity is cyclic, an older mini-halo could coexist with a younger, restarted inner core. We note that our ideas here are no more than toy models; they need to be developed and tested against real, well-observed CCRGs.

Because the observations show that the AGN in every CCRG is “alive”, and because CCRGs are often amorphous, we suggest that small, young sources are being driven by a quasi-isotropic energy flux (as from an unstable jet). Such evolution can be approximated by a self-similar analysis [8]. However, because the edges of the X-ray cavities are not strong shocks (*e.g.*, [9]), we know the expansion is slow; this suggests the expansion proceeds at approximate pressure balance [17]. Such a model predicts the source size  $R(t) \propto (P_j t)^x$ , where  $x$  depends on the ambient pressure gradient. We emphasize that  $P_j$  and  $t$  cannot be determined separately in this model; the best we can do is the limit  $\dot{R} < c_s$ , which gives an upper limit to  $P_j$ .

Because the data also show the radio and X-ray plasmas are well mixed for larger RGs, we further suggest that CCRGs eventually fragment and mix with the ICM. The fragmentation may occur *via* MHD surface effects (such as the tearing-mode instability) which create magnetic filaments or flux ropes. Alternatively, the small-scale flux ropes which we know exist in MHD turbulence may retain coherence and diffuse into the extended ICM in late stages of CCRG evolution. (The ubiquity of filaments in well-imaged RGs suggests such structures are common in general; why should CCRGs be different?) We expect the flux ropes to rise slowly under buoyancy, and to retain their identity for awhile, after which they probably dissipate and merge with the local ICM. In principle,  $P_j$  could be estimated for such a source from the energy content of the radio plasma and its buoyant rise time, but uncertainties in filling factors and flux rope sizes limit the quantitative usefulness of this approach.

### 3.3 The Large Radio Haloes

Some of our radio haloes are large enough to raise the question, where does “CCRG” end and “cluster halo” begin? That is, on what scale is the physics of the full cluster more important than the influence of the AGN? The synchrotron size is one criterion: how large can the radio halo be without needing *in situ* energization? We are skeptical of simple synchrotron-aging estimates, because magnetic fields in the radio source and the ICM are almost certainly inhomogeneous. One can, however, derive a useful limit. The lowest loss rate for the radio-loud electrons is that of inverse Compton losses on the cosmic microwave background. If the electrons spend most of their time in sub- $\mu\text{G}$  magnetic fields, and occasionally migrate into high-field regions (probably a few  $\mu\text{G}$ ) where they become radio-loud, we can find an upper limit to their synchrotron life.

This cartoon predicts the radio plasma in a buoyant flux rope can reach  $\sim 100$  kpc before it fades away. Radio sources larger than this must be undergoing extended, *in situ* re-energization. It follows that some driver other than the AGN must exist on large scales. Ongoing minor mergers are thought to support radio haloes in large, non-CC clusters. They may be important in CC clusters as well (*e.g.*, [16]), and may be driving the larger haloes. But then, if we admit the need for non-AGN heating of CC clusters on large scales, can we be sure that the cooling core itself is heated only by the AGN?

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